Geomorphology of buried glacigenic horizons in the Barents Sea from three-dimensional seismic data

B. RAFAELSEN1, K. ANDREASSEN1, L. W. KUILMAN2, E. LEBESBYE1, K. HOGSTAD3 & M. MIDTBØ4

1Department of Geology, University of Tromsø, N-9037 Tromsø, Norway (e-mail: bjarne@ibg.uit.no)
2Norsk Hydro ASA, 0246 Oslo, Norway
3Norsk Hydro ASA, 9480 Harstad, Norway
4Norsk Hydro ASA, Pb. 7190, 5020 Bergen, Norway

Abstract: The glacigenic sequence of the southwestern Barents Sea shelf has for the first time been studied using 3-D seismic data. The close spacing of 3-D lines and powerful computer workstation interpretation techniques have allowed detailed mapping of the observed features. Several generations of subglacial lineations observed on four different palaeo-surfaces are interpreted to reflect the flow patterns of palaeo-ice sheets. To our knowledge, this is the first time that multiple levels of subglacial lineations have been observed. The lineations are 2.5–8 m in relief, 50 to 180 m wide and 0.5 to 20 km long. All four surfaces show a main lineation pattern comprising lineations with a N-S trend, suggesting that the dominant ice flow was directed northwards across the Barents Sea shelf at least four times during the last 0.8 Ma. Two of the surfaces display semi-circular to oblong depressions trending mainly in the same direction as the sub-parallel lineations. These depressions are 9–53 m in relief, 1.25–3.2 km wide and 1.9–9 km long. In contrast to the buried surfaces, the sea floor is dominated by 2.5–25 m deep cross-cutting iceberg plough-marks from the deglaciation phase of the last Barents Sea ice sheet. The 3-D seismic data are conventional industry data. Despite relatively low seismic frequencies and, hence, limited vertical resolution of seismic profiles, time slices and sub-horizontal time maps are of high spatial resolution, providing detailed images of different stages of buried Quaternary glacial geomorphology.
Kristoffersen 1986; Vorren et al. 1986, 1988, 1989, 1990; Sættem 1992b, 1994; Sættem et al. 1994). This paper presents results from the first use of 3-D seismic data to study the glacigenic sequence of the Barents Sea. The study area, covering 2870 km², is located immediately south of Björnøyrenna at water depths ranging from 250 to 450 m (Fig. 1). Powerful computer workstation interpretation techniques have allowed detailed 3-D mapping and visualization of areas and features of particular interest (Rafaelsen et al. 2000). Detailed interpretation of the 3-D

Fig. 1. (a) Location and bathymetry of the southwestern Barents Sea. The areas with studied 3-D seismic data are indicated by black rectangles. (b) Generalized geo-seismic section, location indicated in (a), outlining the stratigraphy of glacigenic sediments in the study area. Rectangles show the approximate location of two of the 3-D surveys. Modified from Sættem et al. (1992b).
seismic dataset suggests the potential contribution of industry 3-D seismic data to studies of the shallow sediments in the Barents Sea.

The objectives of this paper are, first, to emphasize the value of conventional 3-D seismic data in order to derive detailed morphological information of good horizontal resolution from shallow buried horizons; and, secondly, to focus on how the observed morphological features can help us to understand palaeo-conditions better, in this case the direction of palaeo-ice flow and palaeo-ice sheet extent.

Data and methods

This study is mainly based on 2870 km² of industry 3-D migrated seismic data acquired in 1998 (Lillevik & Lyngnes 1998), made available to the University of Tromsø by the former Saga Petroleum ASA (now Norsk Hydro ASA). 2-D seismic data, industry well logs and shallow borehole logs have also been used with the purpose of stratigraphic correlation to previous seismic studies in the southwestern Barents Sea. Constant velocities of 1500 m s⁻¹ and 1750 m s⁻¹ have been applied for the water and the glacigenic sediment layer above the URU when converting time to depth (Sættem et al. 1992b).

This gives a depth range for the zone of interest of 290–540 m below sea level (bsl).

The three conventional 3-D seismic surveys SG9803, SG9804 and SG9810 (Fig. 1a) were acquired with a depth of source and receiver in the range of 5–8 m. The acquisitions consist of dual sources (flip-flop shooting) with 75 m separation and 6 streamers with 100 m separation (Lillevik & Lyngnes 1998).

With the 3000 m long streamers consisting of 240 channels and a shot point interval of 25 m, the recorded fold is 30 and the recorded bin size is 12.5 m by 37.5 m (inline by cross-line, inlines are orientated parallel to the survey vessel while cross-lines are orientated perpendicular to the inlines). As the applied Hale-McClellan migration algorithm carried out post stack requires input bins to be quadratic, the data were interpolated to 12.5 by 12.5 m. The bin size was finally converted to 25 by 25 m.

The final fold of the data is 20, after spatial decimation from 1440 to 720 channels (30 fold), by common receiver interpolation (60 fold), production of super common mid-point (CMP) input to radon transform demultiple (120 fold) and application of partial stack for the dip-moveout (DMO) and pre stack time migration processors (20 fold). With the applied mute, the processing-generated fold in the glacigenic sediments varies from 1 to maximum 3.

The 3-D seismic surveys SG9803 and SG9804 differ from SG9810 by having a shot point interval of 18.75 m, thus giving a recorded fold of 40. However, the end product is the same; a final fold of 20 and a 25 by 25 m bin size.

### Table 1. Relationship between the present seismo-stratigraphic units defined from 3-D data and earlier work based on 2-D data

<table>
<thead>
<tr>
<th>Horizons / units</th>
<th>Units in Sættem et al. (1992a)</th>
<th>Corresponding units and their ages</th>
</tr>
</thead>
<tbody>
<tr>
<td>bE</td>
<td>b5</td>
<td>5E 22–18 ka (Vorren et al. 1989, 1990)</td>
</tr>
<tr>
<td>bD</td>
<td>b4</td>
<td>4E c. 28 ka (Vorren et al. 1989, 1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b4 &lt; 27 320¹⁴C years BP (Hald et al. 1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I Solheim &amp; Kristoffersen (1984)</td>
</tr>
<tr>
<td>bC</td>
<td>b2?</td>
<td>D₂ 200–130 ka (Sættem et al. 1992b)</td>
</tr>
<tr>
<td>bB</td>
<td>A b1</td>
<td>Younger than URU (&lt; c. 800 ka)</td>
</tr>
<tr>
<td>bA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Early in the processing, the number of samples of the data was reduced by resampling from 2 to 4 ms using a bandpass filter in front with a low cut-off of 6 Hz (24 dB/octave) and a high cut-off of 90 Hz (72 dB/octave) to attenuate the swell noise and to avoid anti-aliasing, respectively. From filter-tests, the highest frequency with geological information in the shallow part is limited up to 80–85 Hz, resulting in a maximum vertical resolution (the ability to distinguish individual reflecting surfaces) of approximately 5 m (=1/4 wavelength). For a dominating frequency of around 40 Hz the corresponding resolution is approximately 10 m.

Velocity analyses were run for every 14 3-D inlines and for every 42 3-D cross-lines to give a square velocity grid of 525 by 525 m. Based on an early phase interpretation of fast-track data, the processing contractor was required to pick velocities on selected target and regional horizons, including the shallow part.

The horizontal resolution (the ability to distinguish separate features on a horizon, given by the post-migrated Fresnel zone; Fig. 2; Brown 1999; Sheriff 1999) is approximately the same as the vertical resolution. Including the relatively high-density grid in the data and the application of the 3-D migration, the total horizontal resolution is good (Fig. 2). By comparison, conventional 2-D migrated seismic data would have an elliptic Fresnel zone (Fig. 2) with improved horizontal resolution only along the line.

In 3-D seismic interpretation, the density of data-points combined with a snap interpretation technique makes it possible to detect sub-sample features. The snap interpretation technique (when searching on maximum amplitude) searches until a true maximum value is found and calculates a sub-sample time value by fitting a quadratic polynomial to the nearest three samples. The peak value of this function is used as a maximum, giving an accuracy of 0.1 ms instead of the sample rate (which is 4 ms). By means of the snap interpretation technique the program can detect the depth of features below the sample interval, explaining why plough marks less than 3 ms (two-way traveltime, TWT) of depth are detectable (Fig. 3). Further, this accuracy is far below the vertical resolution.

The studied 3-D surveys are 16-bit datasets, giving an amplitude range of –32768 to +32767, compared with –127 to +126 in 8-bit datasets. Thus 16-bit datasets give the Automatic Seismic Area Picker (ASAP) more sensitivity in amplitude variation, making the automatic interpretation easier and subtle amplitude variations detectable.

The GeoQuest software GeoFrame 3.8 Charisma IMain, running on a Unix workstation, has been used to interpret the seismic data. Mapping of horizons was achieved mainly by tracing seismic reflections with the ASAP. The ASAP tool provides a more objective way of mapping reflections than hand-drawn interpretations and is able to detect and accurately visualize details on the interpreted horizons. Subtle changes in reflection character that may look like minor disturbances or noise in the seismic section are generally easily recognized on time slices and horizon maps, and may turn out to be interesting geological features that can be traced over significant areas. A good reference is plough marks and lineations (Figs 3 & 4); features which, in the worst case, would not be detected by manual mapping or, at best, would take several days to interpret in detail.

Comparison of maps generated from different specific amplitude extremes, such as maximum amplitude (peak), minimum amplitude (trough) or upper/lower zero crossing (where the amplitude changes from positive to negative, or the opposite), shows that upper and lower zero crossings give the most detailed maps of the shallow palaeo-surfaces. In order to preserve the details from the sub-sampled snap
Fig. 3. (a) Seismic profile showing a cross-section of an asymmetrical curved furrow at the seabed with a ridge of ploughed sediments on each side. (b) An illuminated time–structure map showing the furrow in (a). (c) An illuminated time–structure map with curved furrows in a chaotic pattern. (d) An illuminated time–structure map showing twinned furrows. (e) The approximate location of the illuminated time–structure maps (b), (c) and (d) in 3-D survey SG9804. In all illuminated time–structure maps the light source is located east of the horizons. Colours show depth in ms (two-way traveltime) below sea level.
interpretation, no smoothing has been applied to the final maps.

In addition to application of amplitude information, different attribute maps like instantaneous frequency, reflection strength, cosine of phase, apparent polarity, instantaneous phase, dip and azimuth have been generated in an attempt to extract more information from the dataset regarding specific features.

In the search for geological features not

Fig. 4. (a) Seismic profile showing irregularities on horizon bC in SG9804. The green line represents the interpreted horizon bC. (b) Map with time-structure contours indicating the location of (c) within 3-D survey SG9804. (c) An illuminated time-structure map of horizon bC showing lineations interpreted to be formed subglacially. The ‘footprints’ aligned parallel to the course of the survey vessel (inlines) are artefacts related to the acquisition of the 3-D seismic data. Depth in ms (two-way travel-time) below sea level is shown on the colour bar in (c), but applies for (b) as well. The light source is located east of the horizon and vertical exaggeration (z-axis) is 8×.
related to horizons, a set of volumetric attributes and horizon slices has been generated. For visually enhancing the subtle features, a program called GeoViz has been used (allowing the user to manipulate colours, select the position and aspect of the light source, the vertical exaggeration ($z$-axis) and the angle of the horizon).

So-called ‘footprints’ are artefacts occurring in the 3-D seismic data. They resemble lineations parallel to the inline direction (Fig. 4). The footprints have the same spacing throughout the dataset (with a separation equal to every 12 common mid point lines) and should not be regarded as geological information, but rather as a result of the pattern of movement of the survey vessel.

**Stratigraphy of the glacigenic sequence**

In the study area, the glacigenic sequence is up to 146 m thick. We have identified five seismic horizons (plus seabed) bounding five glacigenic units, termed A (oldest) to E (youngest) (Fig. 5). The oldest seismic unit, A, is only observed in 3-D area SG9810 and is so thin that the lineations observed at its basal reflection are interpreted to be dominated by interference from the seismic response of the top of unit A. The other, overlying younger seismic units, B, C, D and E are separated by pronounced seismic reflectors, here termed horizon bB, bC, bD and bE (bB = base unit B, etc.). The seismic horizons (bA, bB, bC, bD, bE and the sea floor) are here interpreted to represent unconformities formed during several glaciations. The upper regional unconformity is a diachronous surface and is interpreted to be represented by horizon bD in SG9803, bB in SG9804 and bA in SG9810. The seismic units (A, B, C, D & E) probably represent deposition of glacimarine sediments or basal till (Solheim & Kristoffersen 1984). Units A–C in the 3-D surveys are probably of mid-Pleistocene age, whereas units D and E are of upper Pleistocene age (Settem et al. 1992b).

The glacigenic sequence of the southwestern Barents Sea, called the Barents Sea Synthem (Vorren et al. 1989), has been mapped and divided into several seismostratigraphic units (Solheim & Kristoffersen 1984; Vorren et al. 1990; Settem et al. 1992b). A shallow borehole (7222/09-U-01), located close to the 3-D surveys of our study area (Fig. 1), has been correlated to 2-D seismic data by Hald et al. (1990) and Settem et al. (1992a). Their work is the basis for the correlation of our 3-D seismic data to this shallow borehole and to 2-D seismic data from the same area (Fig. 5; Table 1).

Unit A corresponds with unit b1 in Settem et al. (1992b) and is younger than the upper regional unconformity but older than unit B (Table 1). Units B and C (Fig. 5) probably correlate with the lower and upper part of unit b2 of Settem et al. (1992b), respectively. Unit b2 is described by Settem et al. (1992b) as a soft, dark claystone, where the lower part contains structures that may have been formed by iceberg turbation or glaciotectonics. Unit b2 was probably deposited 200–130 ka BP, and the lower part of unit b2 has been interpreted to be deposited in an ice-proximal glacimarine environment whereas the upper part has been interpreted to be a till (Settem et al. 1992a).
Fig. 6. (a) Stratigraphy from the 3-D survey SG9804. (b) Horizon bC from SG9804 shown with time–structure contours, indicating the location of the seismic section in (a). (c–f) Sections of illuminated time–structure maps from the interpreted horizons in 3-D survey SG9804, showing subglacial depressions and different generations of subglacial lineations. A summary of the dominant orientations is shown in Fig. 8 and Table 2. Depth in ms (two-way travel-time) below sea level is given on the colour bars. The light source is located to the east of the horizon and vertical exaggeration (z-axis) is 8×.
According to Vorren & Laberg (1996), most of the southern Barents Sea was deglaciated during the Arnøya Interstadial (29–24 ka BP; Andreassen et al. 1985), when our unit D was probably deposited. A glacier advance just before this interstadial probably formed horizon bD (this paper). Sediments near the base of unit b4 of Sættem et al. (1992), which probably correspond to our unit D (Fig. 5; Table 1), are radiocarbon dated to be younger than 27 320 ± 735 years BP (unit b4 of Hald et al. 1990). This corresponds well with the time frame of the Arnøya Interstadial. Unit b4 of Sættem et al. (1992) is over-consolidated (Sættem et al. 1992b) and corresponds to unit 4E from Vorren et al. (1989, 1990), which is interpreted to be a glaciofluvial sandy sediment, probably deposited by meltwater (Vorren et al. 1989). In addition, unit D (this paper) correlates with sequence I in Solheim & Kristoffersen (1984).

Lineations on horizon bE (Fig. 6) indicate that our study area was again ice-covered, probably in the beginning of LGM I (Late Glacial Maximum I, 24–22 ka BP; Vorren & Laberg 1996). After LGM I, an ice-free period called the Andøya Interstadial (22–19 ka BP) took place, and unit E was probably deposited in this period. Our unit E corresponds with unit 5E from Vorren et al. (1989, 1990; Table 1), which is interpreted to be deposited in a distal glacimarine environment. The sediments may be derived from meltwater rivers in the south and deposited from suspension together with some ice-rafted debris during the ice-free period between LGM I and LGM II (Vorren & Laberg 1996).

Our 3-D seismic data are acquired from an area where other authors (Sættem et al. 1992b; Vorren & Laberg 1996; Lebesbye 2000) have had difficulty in correlating glacigenic seismic units between the eastern and western Barents Sea. The correlation problem is due mainly to the fact that most of the units belong either to a western or an eastern province and wedge out in and around our study area (Figs 5 & 6a). Additional 2-D and 3-D seismic data are required to resolve this problem.

Table 2. Size and predominant orientation of subglacial lineations from the four subsurfaces in 3-D surveys SG9804 and SG9810 (youngest generation first, oldest generation last). The dominant orientations are 349°–50°/169°–230°. No lineations were found on the sea floor in the 3-D surveys. Depth calculated using 1750 m s⁻¹ as the velocity of sound in sediments (Sættem et al. 1992b)

<table>
<thead>
<tr>
<th>3-D survey</th>
<th>Horizon (Fig. 5)</th>
<th>Length</th>
<th>Width</th>
<th>Relief</th>
<th>Dominant orientation Y</th>
<th>O</th>
<th>N°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG 9804</td>
<td>bE</td>
<td>1.2–20 km</td>
<td>100–170 m</td>
<td>2.5–8 m</td>
<td>22° / 202° &amp; 30° / 210°</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>bD</td>
<td>2.5–12 km</td>
<td>60–150 m</td>
<td>2.5–8 m</td>
<td>26° / 206° &amp; 176° / 356°</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>bC</td>
<td>0.8–7 km</td>
<td>60–180 m</td>
<td>3.5–6 m</td>
<td>10° / 190° &amp; 28° / 208°</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>bB</td>
<td>2–7 km</td>
<td>60–150 m</td>
<td>2.5–7 m</td>
<td>50° / 230° &amp; 169° / 349°</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>SG 9810</td>
<td>bE</td>
<td>7–8 km</td>
<td>50–60 m</td>
<td>2.5–3.5 m</td>
<td>48° / 228°</td>
<td>†</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bD</td>
<td>0.5–20 km</td>
<td>50–120 m</td>
<td>2.5–6 m</td>
<td>45° / 225° &amp; 5° / 185°</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td></td>
<td>bA</td>
<td>0.5–20 km</td>
<td>50–120 m</td>
<td>3.5–6 m</td>
<td>45° / 225° &amp; 5° / 185°</td>
<td>†</td>
<td>†</td>
</tr>
</tbody>
</table>
The units defined here are separated by four horizons interpreted to have been formed by subglacial erosion. Features observed on the horizons in the 3-D seismic surveys are mainly negative features (although it is not clear whether the lineations are positive or negative) and have been divided into three main classes: cross-cutting furrows, straight lineations and depressions. The depressions are further subdivided into type I (smooth edges), type II (indented edges) and type III (formed in bedrock) depressions.

Cross-cutting furrows are mainly observed on the sea floor, but a few occur on one of the buried horizons (bE in SG9810). The cross-cutting furrows observed in the study area are interpreted to be iceberg plough marks, and indicate a glacimarine environment.

Straight lineations and depressions are interpreted as indications of palaeo-ice flow directions which, in turn, may be related to palaeo-ice sheet form and extent. The straight lineations are observed on mapped horizons bB to bE and are interpreted to be subglacial bedforms. This implies that warm-based, or at least periodically warm-based, grounded ice sheets have advanced over the study area at least four times. Oblong depressions with similar orientation to the lineations occur on horizon bD in 3-D survey SG9804. The depressions are interpreted as having been formed by subglacial erosion and to record palaeo-ice flow direction, thus supporting the indications from the lineations of dominant palaeo-ice flows towards the north or south.

Cross-cutting furrows (iceberg plough marks)

Description. Curved furrows of negative relief that cross-cut each other in a chaotic pattern are the dominant morphological features on the sea floor (Fig. 3). Similar curved furrows also occur on buried horizon bE in SG9810, but not on any other buried horizon in the study area. The sea floor furrows are 30–500 m wide, 1–20 km long and 2.5–25 m (3–28 ms TWT) deep. In profile, their cross-section is either U- or V-shaped (and sometimes asymmetrical), and some have a small rise on each side (Fig. 3a, b). The relief of the furrows is measured from the bottom of the feature to the top of the flanking rise, or to the surrounding sea floor level if there is no rise on either side of the feature. The furrows usually have a constant depth along the entire feature, and on the sea floor they show a slightly east–west dominant orientation. In some cases, the cross-cutting furrows occur in pairs spaced apart up to 700 m (e.g. Fig. 3d).

Interpretation. The cross-cutting curved furrows are interpreted as representing ploughmarks formed in a submarine environment by drifting icebergs, a phenomenon well known in the literature (Lien 1983; Vorren et al. 1983; Barnes et al. 1984; Stoker & Long 1984; Solheim et al. 1988; Longva & Bakkejord 1990; Dowdeswell et al. 1992; Vogt et al. 1994; Crane et al. 1997; Long & Praeg 1997; Polyak 1997; Solheim 1997). The plough-marks in our study area have a maximum relief of 25 m and are up to 500 m wide and 20 km long. Lien (1983) described plough-marks from the Norwegian continental shelf that are up to 27 m deep, and Crane et al. (1997) mention plough-marks 450–850 m bsl from the southern Yermak Plateau that are up to 10 m deep, and according to Polyak (1997), 15 km long. The largest icebergs may extend deep underwater and have sufficient mass and momentum to force the keel down into the sea floor (Lien 1983). Thus, provided other factors are equal, icebergs reaching the sea floor in deep waters may plough to much greater depths into the underlying sediment than those that run aground in shallower waters. The plough-marks typically have a U- or V-shaped cross-section with a ridge of ploughed sediments on each side (Lien 1983).

The size and shape of the plough-marks...
varies greatly. Buried plough-marks 246 ms below the sea floor have been described from the central North Sea and the Norwegian continental shelf (Long & Praeg 1997). Plough-marks have been observed on the Yermak Plateau NW of Svalbard at depths of up to 850 m below the present sea level (Crane et al. 1997). In the Barents Sea, plough-marks have been found at all depths down to 450 m, although the keels of present-day icebergs rarely exceed 100 m (Solheim 1997).

Paired furrows observed in our study area (Fig. 3d) are interpreted as having been formed by icebergs with two keels, each forming separate plough-marks, a phenomenon described previously by Barnes et al. (1984) and Longva & Bakkejord (1990). Our observations imply that the iceberg forming the largest paired plough marks in the 3-D surveys was at least 700 m wide at the sea floor.

Plough-marks commonly occur on the sea floor in the study area, but only a few were found on buried horizon bE in SG9810. The reason why plough-marks are not found on other buried horizons is probably that subsequent glaciations have removed previously positive relief of less than 1 m, widths of 4–8 m, lengths typically 100–500 m, and are thus much smaller lineations than those observed on our buried horizons. From the Ross Sea continental shelf, Antarctica, lineations described to be 100–200 m wide, up to several tens of kilometres long and with a relief of the order of several metres are interpreted as mega-flutes (Shipp & Anderson 1997).

Some of the straight lineations in the 3-D seismic areas occur in bedrock and may resemble grooves. Pudsey et al. (1997) describe grooves from the Antarctic Peninsula shelf with relief of 2–3 m offshore and 10–20 m inshore at 200–700 m water depth. Bennett & Glasser (1996) interpret glacial grooves, ranging from a few metres to several kilometres long, to be streamlined depressions formed by aerial ice flow. Other authors refer to grooves that were probably formed by subglacial erosion with meltwater as the active erosive agent (Kor et al. 1991; Rains et al. 1993), but the features they describe are not as straight and persistent as the lineations in our 3-D datasets. Morphologically, glacial grooves are comparable to glacial striations, except that grooves are larger and deeper (Bennett & Glasser 1996). Both glacial striations and grooves indicate the direction of local glacier movement and indicate a warm-based glacier. Based on the above discussion, we cannot exclude the possibility that some of the lineations on the upper regional unconformity are grooves.

In recent years, continental lineations composed of glacial sediment have been recognized on satellite images (Punkari 1993, 1997; Boulton et al. 1993), but the features they describe are not as straight and persistent as the lineations in our 3-D datasets. Morphologically, glacial grooves are comparable to glacial striations, except that grooves are larger and deeper (Bennett & Glasser 1996). Both glacial striations and grooves indicate the direction of local glacier movement and indicate a warm-based glacier. Based on the above discussion, we cannot exclude the possibility that some of the lineations on the upper regional unconformity are grooves.
Fig. 9. (a) Seismic profile showing buried type I depressions in the northwestern part of 3-D survey SG9804. (b) An enlarged area of (d), showing type I depressions. (c) Seismic profile showing buried type II depressions in the northeastern part of 3-D survey SG9804. (d) Illuminated time–structure map of horizon bD. White arrows indicate the main orientations of the lineations and their relative age ($26^\circ$/206$^\circ$ = youngest, 176$^\circ$/356$^\circ$ = oldest). Depth in ms (two-way travel-time) below sea level is shown on the colour bar. The light source is located east of the horizon and vertical exaggeration (z-axis) is 8 ×.
et al. 2001) and classified as mega-scale glacial lineations (Bennett & Glasser 1996). Typical lengths range between 8 and 70 km, widths between 200 and 1300 m and the spacing between lineations may vary between 300 and 5000 m. On the ground, their morphology is often difficult to detect. According to Clark (1993), mega-scale glacial lineations are formed by differential subglacial sediment deformation caused by variations in bed characteristics, and their long length reflects rapid ice flow and/or long periods of time for development. Using late Quaternary chronologies for the James Bay lowlands, where mega-scale glacial lineations were generated by the last Laurentide Ice Sheet, Clark (1993) concluded that these large streamlined landforms were produced by a fast-flowing glacier at velocities typical of modern ice streams (400–1600 m a⁻¹). On land in northern glaciers where old lineations are obliterated during ice sheet retreat. 

Two kinds of incised semi-circular depressions are observed on horizon bD in 3-D survey SG9804, and a third kind is observed on the horizon bB (URU) in the same 3-D survey. Type I depressions (Fig. 9a & 9b) are 35–53 m (40–60 ms TWT) deep, 1560–1875 m wide and 1875 to more than 9000 m long. Their long axes are orientated 26º/206º. These depressions have a concentric shape, are widest in the middle and become narrower as they shallow. Their deepest point is slightly NNE of their centre. A common feature of the depressions is that they have a smooth surface and even edges, which are not marked by the straight lineations that are observed on the surface surrounding the depressions.

Type II depressions (Fig. 9c & 9d) are relatively shallow, 3750–5625 m in length, 1250–1700 m in width and 9–32 m (10–37 ms TWT) in depth. Their longest axes are orientated 87º/188º and 169º/349º. They are elliptical in shape, deepest in the middle and become shallower towards the edges. The edges are rough and indented and some of the depressions seem to occur in series, where the depressions are mostly aligned parallel to each other, resembling an
en echelon pattern (Fig. 9d). All of the depressions in such a series are about the same size.

Type III depressions are observed on the horizon bB (URU) in SG9804, in early Cretaceous bedrock (Fig. 6e). They are semi-circular with a slight north–south trending elongation, ranging from 3125–3200 m in width, 3500–3850 m in length and 9–13 m (10–15 ms TWT) deep. Their edges seem to be a combination of type I and II depressions, in that they have relatively smooth edges even though the lineations on the horizon reach their edge (Fig. 6e). This is caused by the fact that the depth of the lineations gradually decreases as they reach the edge of the depressions.

Interpretation. The depressions (Figs 6e & 9) are thought to have been formed by subglacial erosion. After the depressions were formed, they may have been modified by meltwater. Type I depressions (Fig. 9a & 9b) may have formed either coeval with or after the formation of the straight lineations, since the depressions have smooth edges. We believe that it is most likely that the type I depressions formed after the nearby lineations, mainly because their orientations differ significantly. Depressions with their deepest point NNE of their centre may indicate that the glacier moved towards the NNE, but ice flow in the opposite direction cannot be ruled out from the morphological observations alone.

Type II depressions (Fig. 9c & 9d) may have been formed in both directions along their longest axis as their deepest point is in their centre. The depressions were probably formed before the straight lineations because the straight lineations extend all the way to the edge of the depressions, making the edges rough and indented. If these interpretations are correct, type II depressions are probably older than the lineations and type I depressions are younger than both lineations and type II depressions. Another possibility is that both type I and type II depressions formed before the lineations, but later only the eastern part of the 3-D survey (type I depressions) was modified by meltwater.

Type III depressions (Fig. 6e) may indicate ice flow towards the north or south, but because they are so rounded this is speculative. They may have been formed in areas where the bed was easier to erode.

Depressions formed in bedrock by subglacial erosion vary in size from a few metres to several hundred metres in diameter (Bennett & Glasser 1996). Subglacial meltwater erosion in unconsolidated sediments is also thought to have formed depressions of about 200 m in diameter (Rampton 2000); such depressions formed in bedrock are called S-forms and are about 0.5 by 1 km (Beaney & Shaw 2000). Negative, longitudinal forms formed by meltwater erosion are called spindle flutes in the classification of Kor et al. (1991), regardless of size. They are narrow, shallow negative forms that are longer than they are wide. They become slightly wider downstream and may be asymmetrical. The shape of these spindle flutes is similar to type II depressions on horizon bD in SG9804 (Fig. 9c & 9d). Examples of eroded depressions (S-forms) formed by meltwater are described from Alberta (Beaney & Shaw 2000) and from the northeastern coast of Georgian Bay, Canada (Kor et al. 1991). The depressions observed in this study are interpreted as having been formed by erosion beneath a warm-based ice sheet, and some (especially type I depressions) are suspected to have been modified by meltwater.

Discussion

The morphology of the buried surfaces of late Cenozoic age, including the upper regional unconformity (URU) that separates the upper unconsolidated sediments from underlying consolidated rocks (bedrock), suggests that extensive glacial erosion and deposition has taken place in the study area.

Palaeo-ice flow and extent

Interpretation of 3-D seismic morphological features of the four buried horizons of the study area provides important information about glaciations and deglaciations in the southwestern Barents Sea.

Glacial advances. The existence of subglacial lineations on the four main buried horizons of our study area (horizon bB, bC, bD & bE; Fig. 6; Table 2) indicates at least four glacial advances in the southern Barents Sea. In addition, there may have been a glacial advance prior to these four, as horizon bA is interpreted to represent the URU. Unfortunately, the morphological features on horizon bA are questionable. On the horizons bB, bC, bD and bE the large size and persistence over several tens of kilometres of the lineations suggests that they were formed subglacially. Their orientation indicates that ice flow directions mainly towards north and NNE (or south and SSW) were present in all four glacial advances. The slightly different orientations of the two sets of lineations on all four buried horizons of 3-D
Fig. 10. (a) Extent of ice sheet during advance 5 (LGM II; Vorren & Laberg 1996). (b) Hypothetical extent of ice sheets during retreats 1 to 4 proposed in this study.
areas SG9804 and SG9810 (Table 2) may reflect different ice-flow patterns.

An ice-flow direction towards the west has previously been suggested for the study area during glacial maxima when the ice sheet reached the shelf edge (Fig. 10a; Landvik et al. 1990; Vorren et al. 1990; Vorren & Laberg 1996).

Most of the features in our study area are orientated north–south, and both bathymetry, sub-aerial topography and ice-sheet modelling (Dowdeswell & Siegert 1999) suggests an ice-flow direction towards north. The Bjørnøysyrenna is relatively deep (up to 500 m below present sea level) and may have acted as a calving bay during a glacial retreat. The observed lineations and depressions may have formed during an ice-sheet retreat (Fig. 10b), when Bjørnøysyrenna was ice free, obliterating features formed during the earlier stages of glaciation. Though it is less likely, the possibility that the oldest generation of lineations on a horizon have formed during a glacial advance and been preserved beneath the ice sheet, while the youngest generation of lineations were formed during deglaciation, cannot be excluded. A third possibility is that these features were formed while the ice sheet reached the shelf edge, and that ice flow turned from trending north–south in our study area to a more east–west orientation when entering the Bjørnøysyrenna. Lineations in unfossilized glacigenic sediments beneath a warm-based ice sheet are probably degraded relatively rapidly, and we believe that it is more likely that older generations of lineations and depressions have been removed and that just the last couple of generations descendent from deglaciating phases (Fig. 10b) have been preserved.

Plough-marks

The plough marks on the sea floor indicate a glacimarine environment. Their chaotic cross-cutting pattern shows a slightly east–west dominant orientation, suggesting that the prevailing wind and ocean-current direction in the study area were towards the east or west. When the study area was ice free, but still proximal to the ice, katabatic winds and melt-water discharge may have affected the direction of iceberg drift. Vorren et al. (1990) indicate that Bjørnøysyrenna, and part of the area just south of Bjørnøysyrenna, may be among the first parts of the southwestern Barents Sea to become ice free during ice retreats, thus forming a large iceberg-free bay. In this bay, the current direction is likely to have been towards the east in the southern part and towards west in the northern part of the bay (Vorren et al. 1990). In the early stages of the deglaciation, the dominant direction of iceberg drift may have been east–west trending, but as larger parts of the southwestern Barents Sea became ice-free the direction of iceberg drift became more chaotic.

Conclusions

1. The present study illustrates that conventional industry 3-D seismic data, acquired for the purpose of studying deeper targets, can provide detailed morphological information on shallow buried glacigenic sequences.

2. The morphology of the buried horizons, together with the repeated glacigenic sequence, suggests that extensive erosion and deposition has taken place.

3. Long straight, negative lineations observed on four buried horizons, are interpreted as having formed beneath a warm-based ice sheet, reflecting the dominant ice-flow directions. The lineations provide conclusive evidence that grounded ice has reached the southern part of Bjørnøysyrenna at least four times since the formation of the upper regional unconformity.

4. A dominantly north–south orientation of glacial lineations observed on all buried horizons suggests that they were formed during ice sheet retreats.

5. Plough-marks occur mainly on the sea floor and indicate that icebergs have reached depths of 456 m below present sea level, and that some icebergs were up to 700 m wide at the sea floor.

Norsk Hydro ASA and the European Communities project TriTex (IST–1999–20500) are acknowledged for funding the research project. Norsk Hydro ASA, Statoil ASA, Norsk Agip A/S, Fortum Petroleum A/S and former Saga Petroleum ASA are acknowledged for providing the seismic and well data. The University of Tromsø acknowledges support from GeoQuest via computer software and help on technical issues. We offer our sincere thanks to D. Praeg and A. Solheim who critically reviewed the manuscript and to P. E. B. Armitage who corrected the English language.

References


B. RAFAELSEN ET AL.

RAFAELSEN, B., MIDTBØ, M., KULIMAN, L. W., LEBESBYE, E., HOGSTAD, K. & ANDREASSEN, K. 2000. 3-D seismic data used to investigate the Late Cenozoic sediments of the southwestern Barents Sea. Geonuty, I. 139.


